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Concentrator Testing Using Projected Images

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CONCENTRATOR TESTING USING PROJECTED IMAGES

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SUMMARY

A solar concentrator intended for the Space Station Freedom solar dynamic power system was tested at NASA Lewis Research Center. The optical measuring system for aligning the concentrator used a panel of lights, a digitizing camera, and computer algorithms to evaluate the concentrator optical properties. Since this system indirectly measured concentrator properties, a simple, direct, check system was needed to verify the results. The solution was to install a light source at the concentrator focal point. The light source illuminated the entire concentrator, and the parabolic concentrator reflected parallel rays to produce a parallel projection of the reflective concentrator facets onto the ceiling of the test facility. After correcting for an error in this system, the two optical systems were in good agreement. Subsequent testing showed that the focal-point-light-source-ceiling image system also provided considerable information about the quality of the reflective surface.

INTRODUCTION

The solar dynamic system developed for Space Station Freedom used a parabolic concentrator to reflect solar energy into a cylindrical receiver cavity. This solar energy heated a gas to rotate a turbogenerator to produce electric power. The solar concentrator is aligned on the ground, disassembled for launch to low Earth orbit, and then reassembled in space. Considerable optical testing is required to ensure that the concentrator will be able to hold its alignment and perform properly in space.

An optical alignment system was developed by McDonnell Douglas Space Systems Company for concentrator alignment for their terrestrial solar dynamic program. This system was called a digital image radiometer (DIR) because digital images of the concentrator were processed to measure the concentrator optical alignment and predict performance with solar radiation. The DIR system uses a panel of small lights, a video camera, an image processor, and a computer processing system. Each light illuminates the entire concentrator, but only small areas of the concentrator reflect this light back to the camera. The computer processing system determines the orientation of these small areas that reflect each light back to the camera, based on the location of each light, the locations of the small areas, and the location of the camera. The lights are sequentially turned on, and by combining the orientations of each small area, the contour of the entire concentrator is determined.

Since the DIR system indirectly measures concentrator properties, a simple, direct, check system was needed to verify the results. A new optical evaluation system using projected images was developed for this purpose and is presented herein.

DESCRIPTION OF PROJECTED IMAGE SYSTEM

A high-intensity light source was mounted at the concentrator parabolic focal point to linearly project images of the reflective concentrator facets onto the ceiling of the test facility. This system is illustrated in figure 1. The light source illuminates the entire concentrator. Light paths start at the parabolic focal point, go to each of the facets, and then to the ceiling. If the facet contours exactly match the ideal parabola, the reflected rays will all be parallel and the projections will be exactly linear. Deviations of the ceiling images from the linear projections represent deviations of the facet contour from the ideal parabola. These deviations result from the approximations used in the concentrator design and from errors in the facet contours. Knowledge of the deviations in the facet contour permits prediction of the ceiling image and, conversely, analysis of the ceiling image provides facet contour information.

Note that the light paths in the projected image system are exactly the opposite of the light paths that exist during normal concentrator operation. In normal operation, parallel light rays are reflected by the concentrator surface to the focal point. In this system, light from the focal point is reflected by the concentrator as parallel reflected rays.

The ceiling image system is shown during operation in figure 2. The concentrator, with 49 of the intended 456 facets, is at the bottom of the photograph. The light source, a filament less than 1 in. long, is shown in front of the American flag. This light source appears large because the ceiling lights were off and the camera film was saturated by the light. Images of the triangular facets are reflected onto the ceiling. The variations in size and shape of these facet images occurred because the facets deviated from the ideal parabolic contour. These deviations were magnified by the approximately 60-ft projection distance from the facets to the ceiling.

IMAGE SYSTEMS TESTING

DIR testing began with facets scattered to enable evaluation of this system's capabilities in all parts of the concentrator. The initial ceiling image test used this same configuration to compare the operation of the two systems. Facet outlines based on DIR data were compared to the actual facet images.

Comparison testing was done with the 49 facets scattered on the concentrator as shown in figure 3. Two or three facets were on each hexagonal panel. The black area at the top of this photograph is the panel of lights for the DIR system. Output from the DIR system included facet pointing errors in two directions and facet contour radii of curvature in two axes. This output was subsequently used as input to a portion of the OFFSET code [1]. Subroutines were added to the OFFSET code to generate an expected outline of the ceiling image of each facet from a focal point light source. These outlines and the actual facet images from the ceiling image test are shown in figure 4. There is a systematic deviation of all the facet images from the black outline. This deviation varied from over 15 in. near the vertex to under 10 in. on the right side of the photograph. In both cases, near the vertex and on the right side, the image deviation could be explained by an 8-in. deviation of the light source from the focal point. The analysis was repeated inputting a light source position 8-in. away from the focal point. The result was the excellent agreement of the black facet outlines and the facet images shown in figure 5. The systematic error appears to be completely corrected.

The light source hardware was next investigated. Indeed, the light source was observed to be several inches from the centerline of the concentrator. The source of the problem was that the power and support cables were entwined as shown in figure 6. The light source position error was subsequently surveyed to be approximately 8 in. and was corrected by properly installing the light source power and support cables.

An inspection of figure 5 reveals an error in the size and shape of a few facet images. These images are elongated in a direction at 45° to the ceiling grid as compared to the computed outlines, indicating a flattening of the facets in this direction. Because the inputs from the DIR system to the OFFSET code are only measured in the two axes parallel to the ceiling grid lines, off-axis distortions were not included in the computed outlines. Although a residual distortion error exists, there is obvious agreement between the DIR system and the projected image system in the location and shape of the facet images.

FACET ROTATION TESTING

The facet rotation testing employed the rotation of individual facets to highlight facet nonsymmetries for ceiling image testing. For this test, six facets were installed in one hexagonal panel as shown in figure 7. These represented three types of facets that were developed for the solar concentrator. The facet at the 1 o'clock position is a STAR facet. STAR (solar thermal advanced reflector) is the newest facet and has an improved (more specular) surface. The facets at 3, 5, and 7 o'clock are silverlux SCAD facets. All but two of the 49 facets in the SCAD (solar concentrator advanced development) program were coated with silverlux reflective film. The facet at 9 o'clock is also a silverlux SCAD facet and has an oil smear on its surface. The facet at 11 o'clock is one of the two VDA (vapor-deposited aluminum reflective surface) SCAD facets.

The images of the six facets are shown in figure 8. Because of the reflection, the relative positions of the six facet images are reversed. The STAR image is at 11 o'clock; the three silverlux images, at 9, 7, and 5 o'clock; the silverlux image with the oil smear, at 3 o'clock; and the SCAD VDA image, at 1 o'clock. Note that the STAR image is somewhat larger and has a sharper triangular outline than the other images. The larger size results from the STAR facet surface contours, which have larger radii of curvature than the contours of the other facets. The STAR image also has a sharper triangular outline because the facet surface is more specular. The smeared facet at 3 o'clock reflected significantly less light than the other facets. Irregularities in the facet outlines are caused by slope errors in the facet contours.

Images of these six facets are shown again in figure 9, but the facets were rotated in place by 120° from the position photographed in figure 8. The facet images are still in the same places: the STAR is at 11 o'clock; the VDA, at 1 o'clock; the smeared silverlux, at 3 o'clock; and the other silverlux images, at 5, 7, and 9 o'clock. The size and shape of all the facet images have changed significantly from the previous photograph. These changes were the result of nonsymmetric deviations of the facets from the design spherical contour.

These six facet images are shown in figure 10 after a second rotation of 120°. An overlay indicates the ideal image of the hexagonal panel as solid lines and outlines of facets with the design spherical contour as dashed lines. Deviations of the facet image shapes from the design spherical shapes result from contour error and deviations of the facet image position result from facet pointing error.

Outlines of the facet images from figures 8 to 10 are shown in figure 11. Note that some images varied considerably after the facets were rotated. This variation was caused by nonsymmetries in the contour of the facets, although they had all been designed to have a symmetrical spherical contour.

CONCLUDING REMARKS

The ceiling image system augments and verifies the digital-image-radiometer (DIR) optical measuring system.

Correct operation of the ceiling image system depends primarily on proper alignment of the light source relative to the solar concentrator. Gross misalignment of the light source is readily detected, as was demonstrated during initial operation. An 8-in. misalignment of the light source created a significant discrepancy between the outlines computed (based on DIR data) and the actual facet images. This was immediately recognized as a misalignment of the light source.

The ceiling image system provides a quick visual check of facet contour, alignment, specularity, and symmetry. Deviations of facet contour are apparent as variations of the shape of the facet images. Alignment errors cause the facet images to be positioned differently from the expected linear projection of the facet. Facet specularity is apparent in the sharpness of the facet outline. Facet symmetry can be determined by comparing the facet images after the facet has been rotated. Other miscellaneous information can also be gleaned by careful examination of the facet images.

REFERENCE

[1] Jefferies, K.S., "Ray Tracing Optical Analysis of Offset Solar Collector for Space Station Solar Dynamic System," 23rd Intersociety Energy Conversion Engineering Conference, Vol. 4, ASME, pp. 225-232: 1988. (Also, NASA TM-100853).

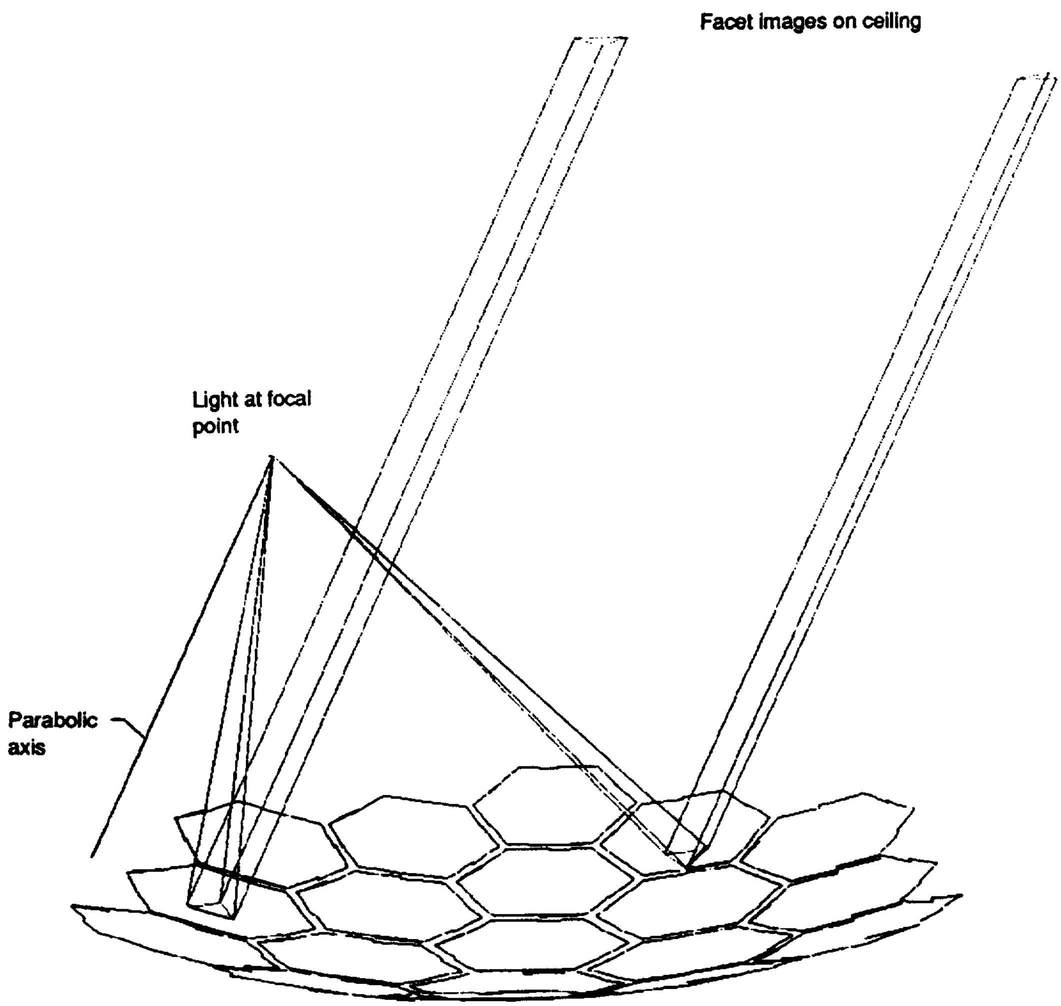

Figure 1.— Projected image optical system.

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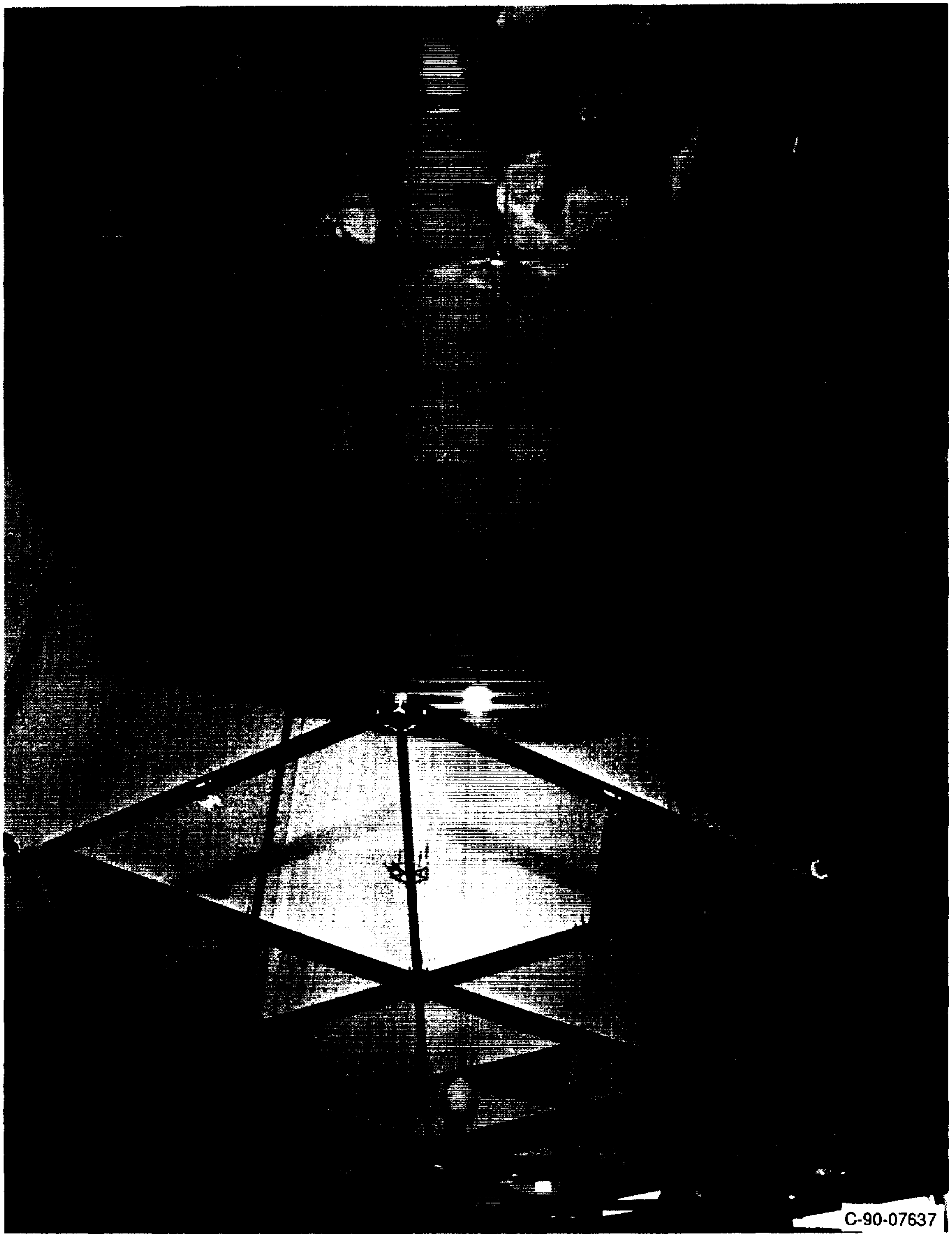

Figure 2.— Ceiling image system during operation.

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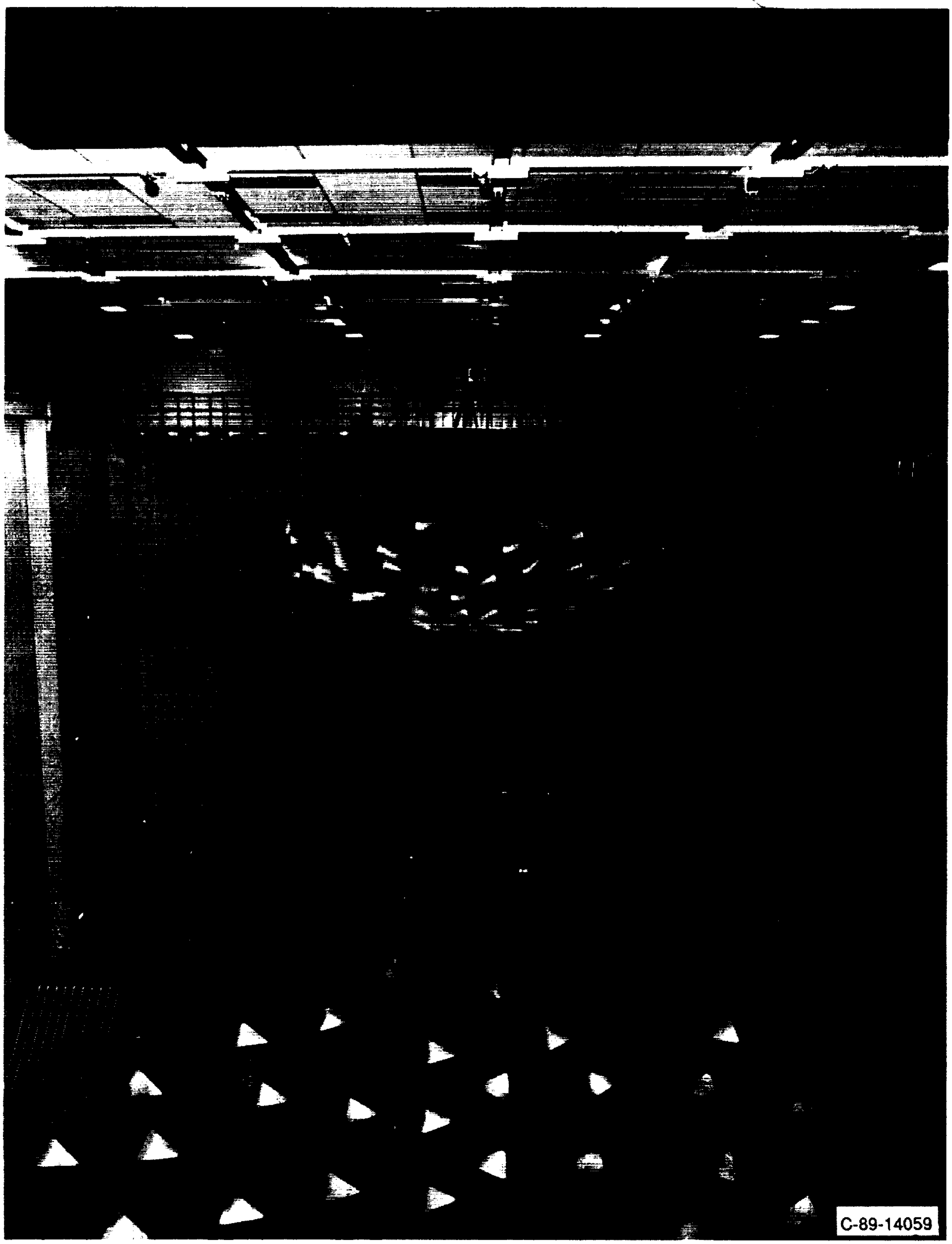

Figure 3.— Concentrator with scattered facets.

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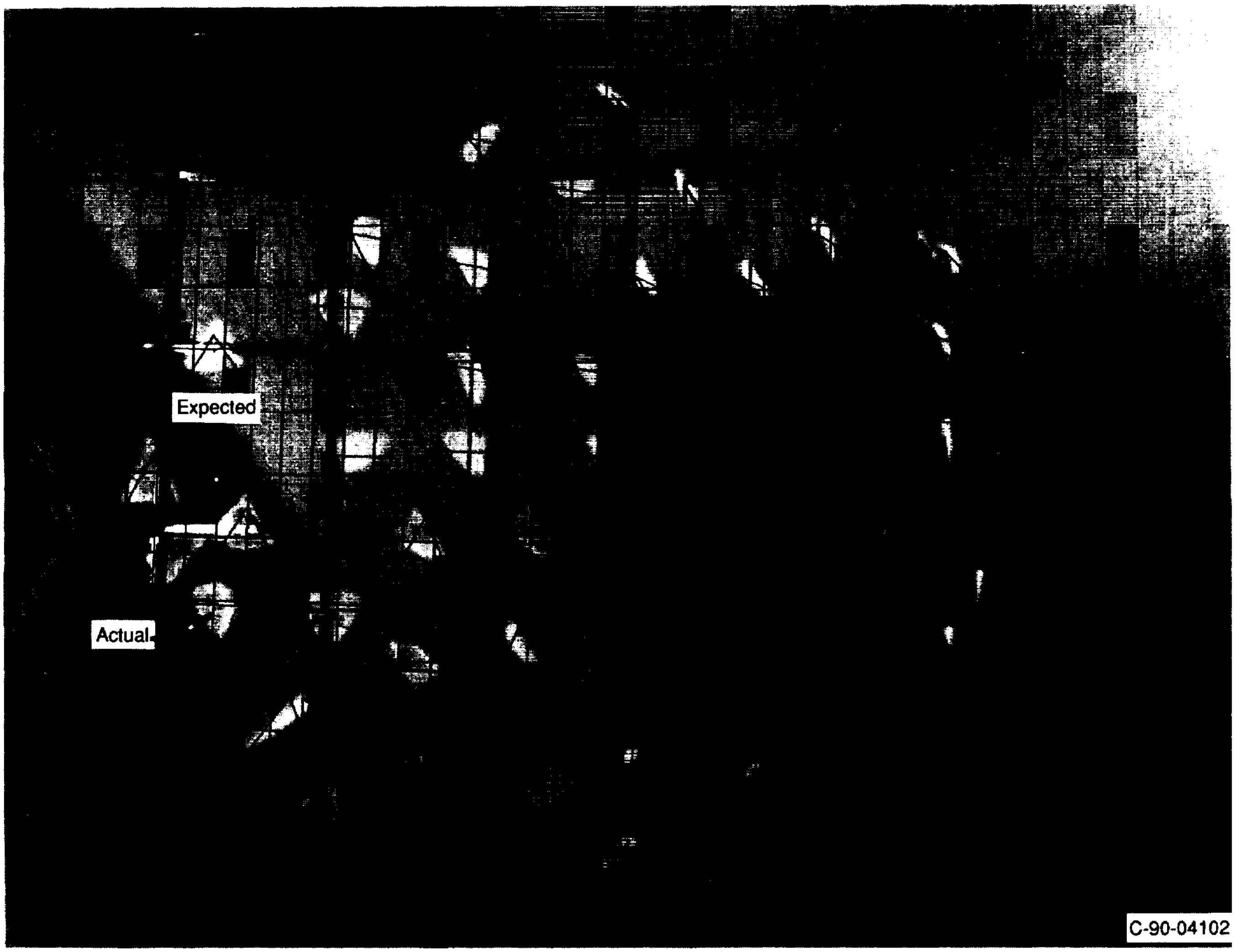

Figure 4.— Actual ceiling images and expected outlines.

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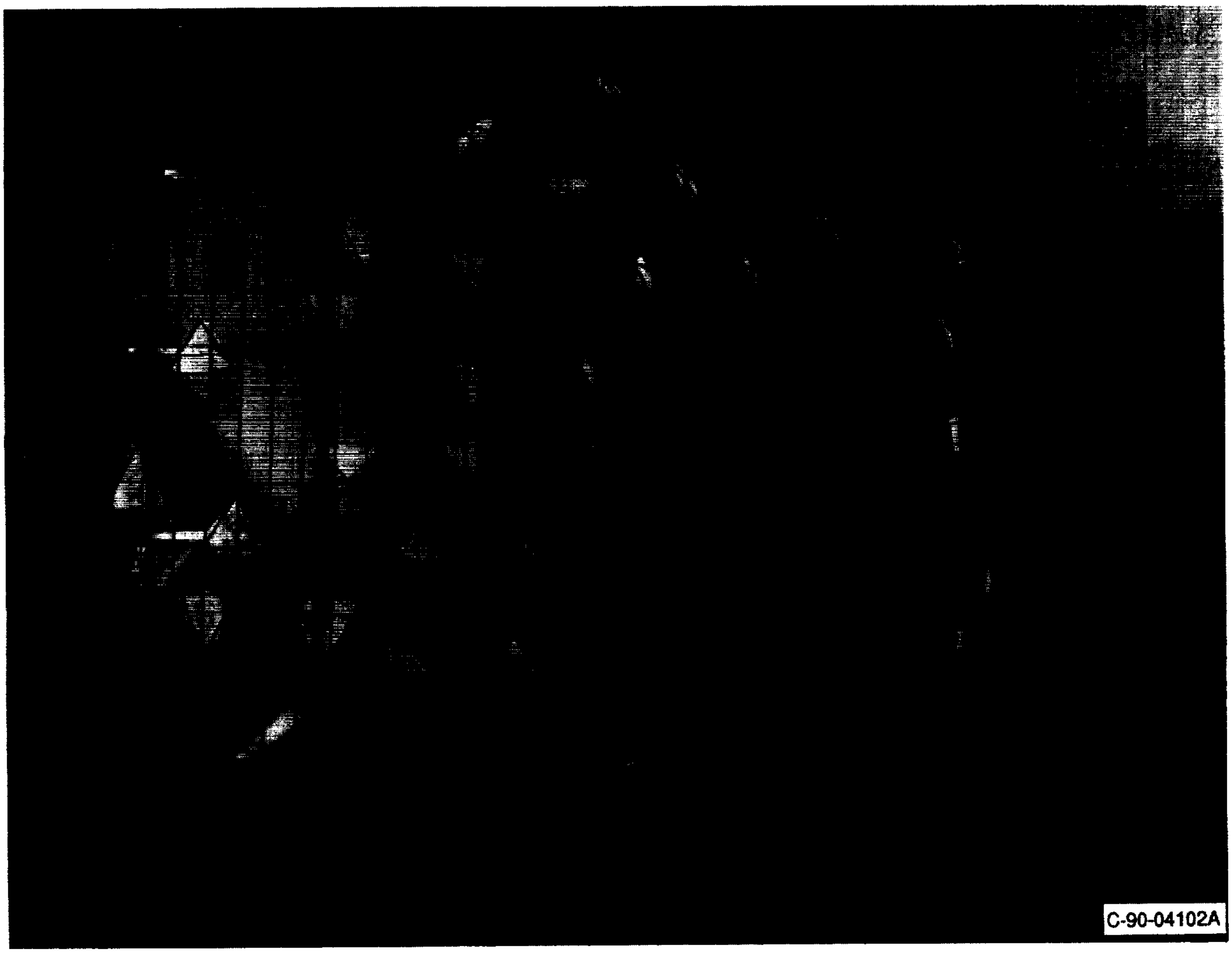

Figure 5.— Ceiling images and corrected outlines.

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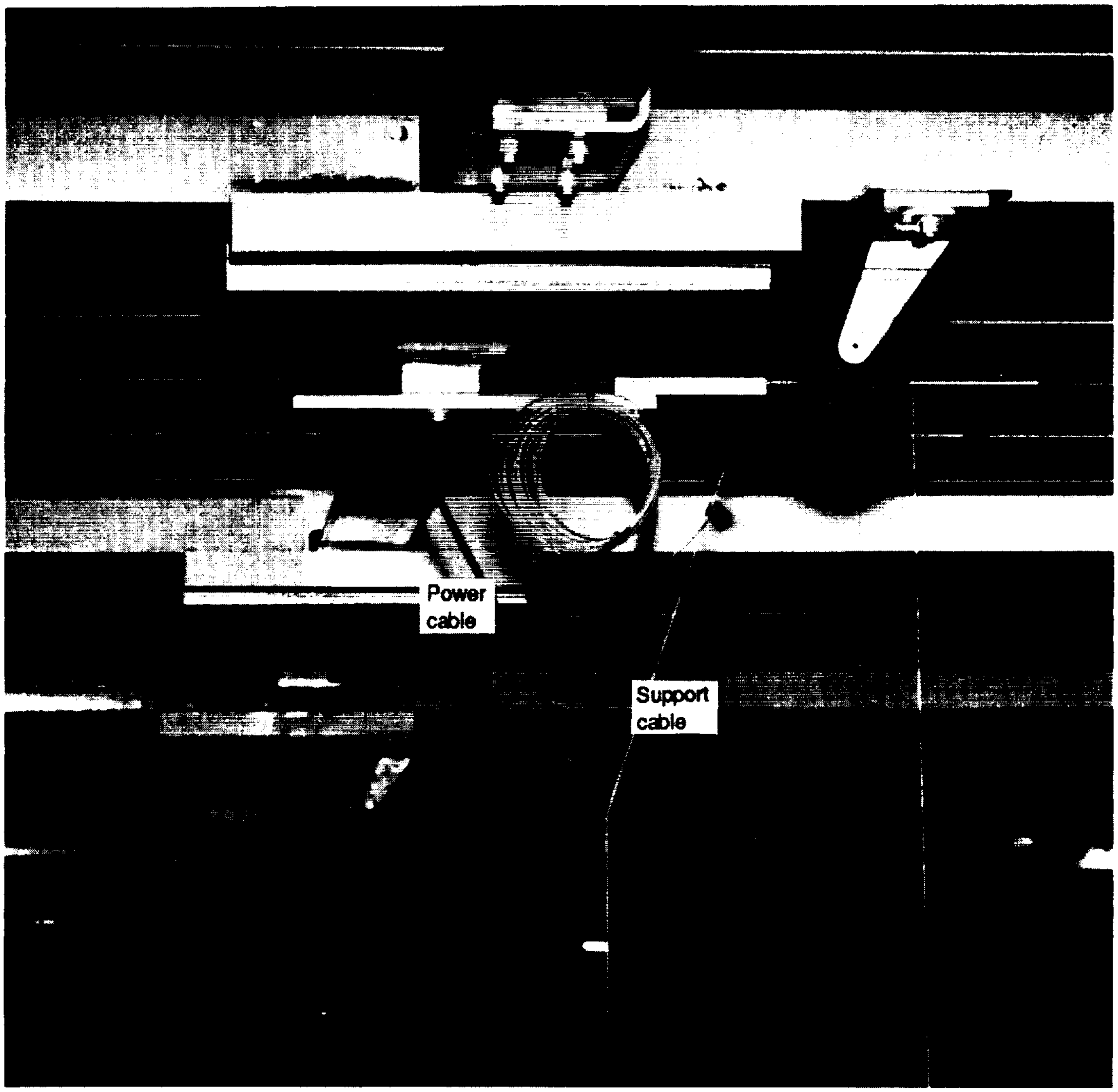

Figure 6.— Focal point light power and support cables entwined.

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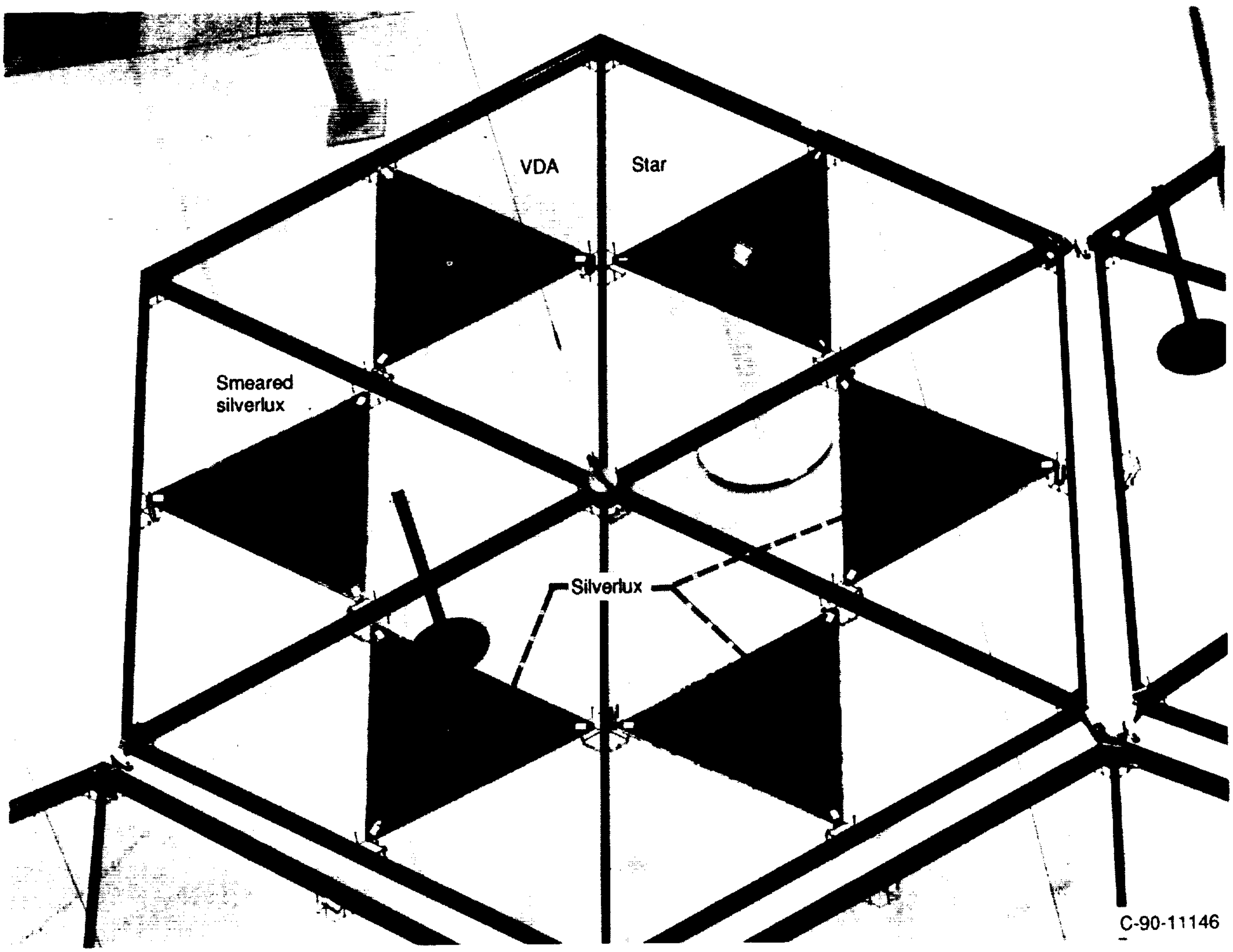

Figure 7.— Six facets installed in one hexagonal panel.

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Figure 8.— Ceiling images of six facets.

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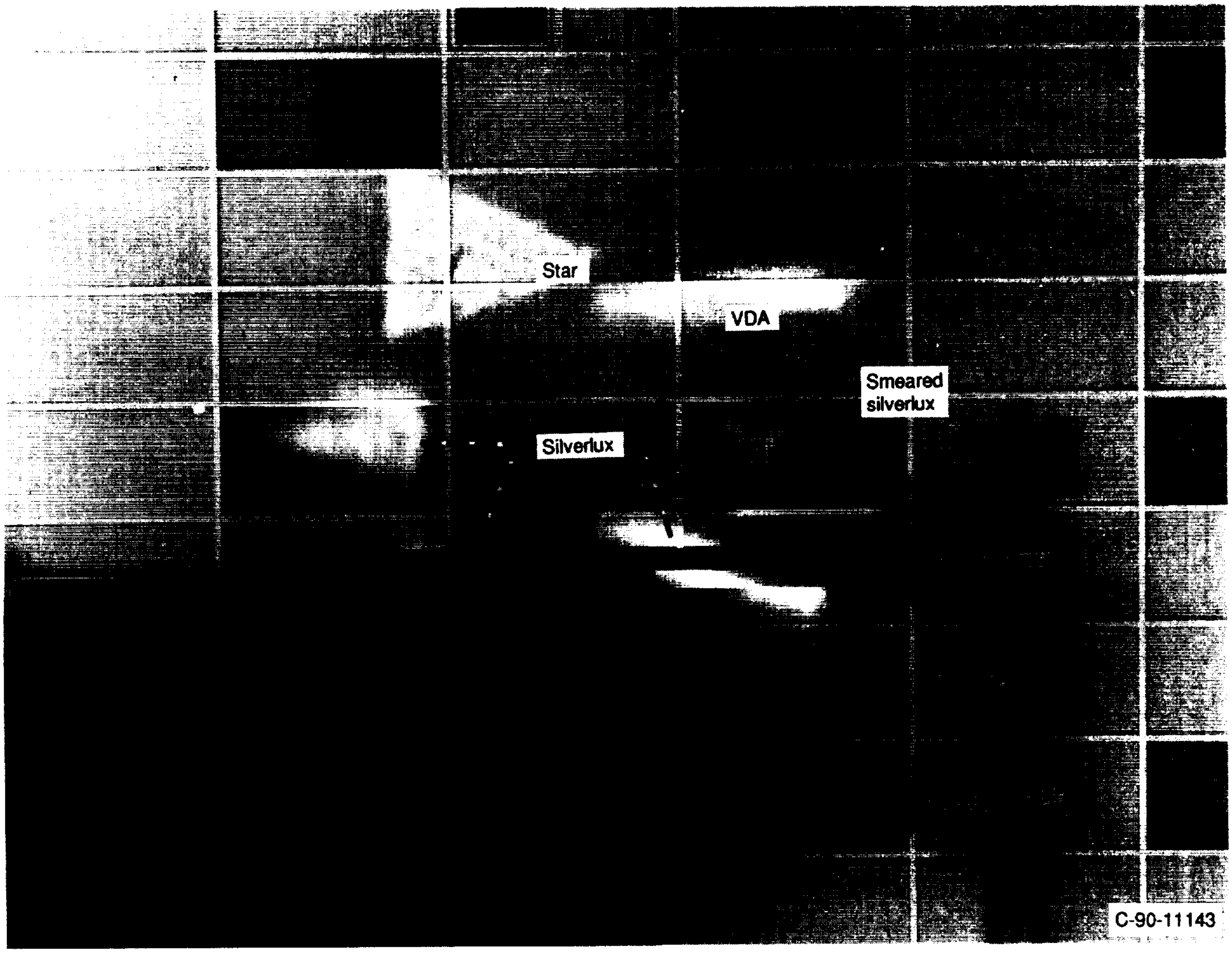

Figure 9.— Ceiling images after six facets were rotated 120°.

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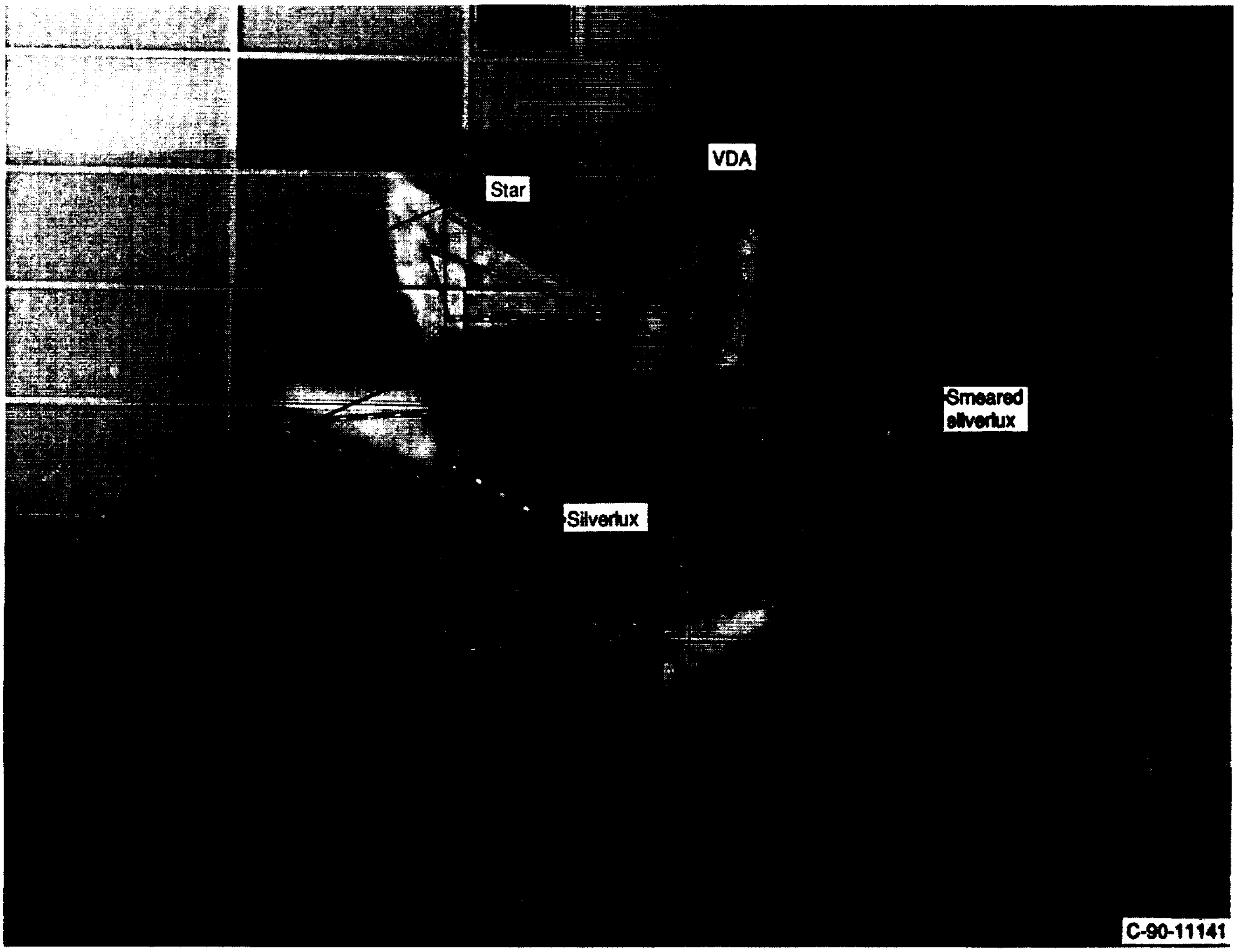

Figure 10.— Ceiling images after a second 120° rotation, with design outlines (dashed lines).

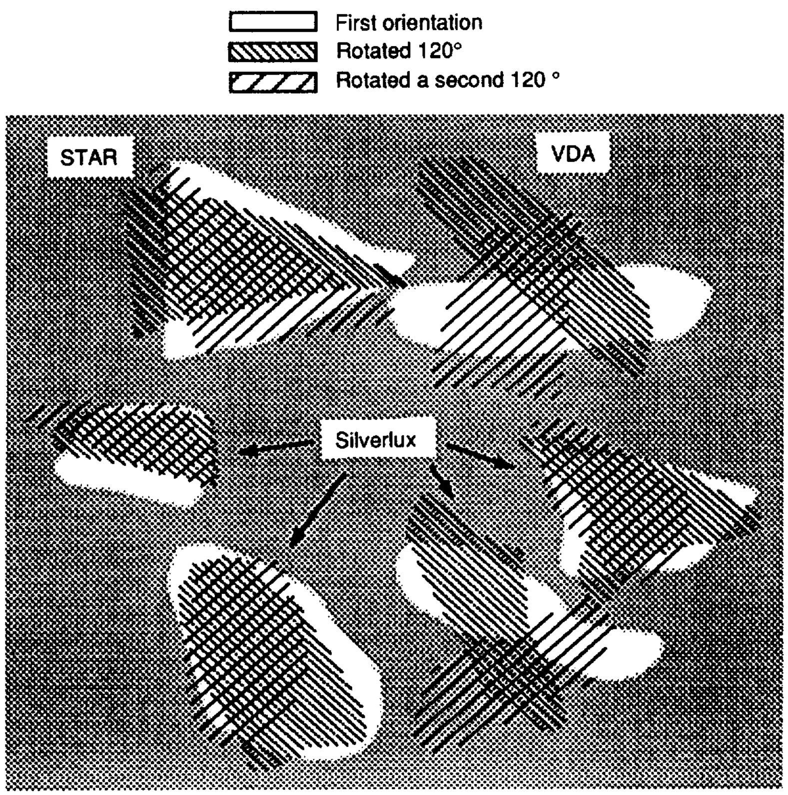

Figure 11.—Outlines of facet images for three rotations.

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16. Abstract
The projected image system can be used to evaluate concentrator optical properties by comparing images reflected onto the ceiling of the test facility to theoretical facet outlines. This system was tested by comparing ceiling images to facet outlines computed using facet characteristics measured by the digital-image-radiometer (DIR) optical measuring system. The agreement was good, confirming the accuracy of both optical systems. Six facets were mounted in the centers of the pie sectors of one hexagonal panel. Differences between the facets and facet nonsymmetries were observed in photographs of the ceiling images of these facets.

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